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GEORGE R. BROWN CONVENTION CENTER

APPLYING THE ENERGY INSTITUTE AND GMRC/PRCI GUIDELINES FOR THE AVOIDANCE OR REDUCTION OF VIBRATION PROBLEMS IN SMALL DIAMETER PIPING BRANCH CONNECTIONS

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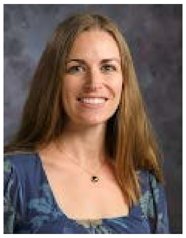
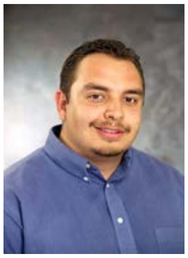


Ms. Simons performs thermal and acoustic analyses of compressor and pump piping systems as well as solving flow and acoustic problems of various types of piping—steam and gas turbines, blowdown and other facilities. She also leads flow pulsation research. She leads flow pulsation research that has included extensive testing to advance technology and available tools in areas such as FIV. Ms. Simons is a lead researcher in developing guidelines for GMRC in the areas of pulsations in mixed compression stations and surge force predictions. Ms. Simons has presented short courses, tutorials, and technical papers on acoustics, pulsations, and vibrations at various industry conferences.



Mr. Fierro has experience in the fields of mechanical vibrations, finite element analysis, acoustics, and compressor and piping system design. He performs mechanical system analyses with the aid of ANSYS and CAESAR II to predict vibrational mode shapes and frequencies, vibration amplitudes, and related dynamic and thermal stresses. He also performs acoustic analyses of complex piping systems to optimize the acoustical responses to minimize adverse pulsation effects on compressor performance, system pressure drop, and piping vibration and related stresses. These analyses have been performed on existing and planned compressor installations.

Mr. White is experienced in the fields of mechanical vibrations, static stresses, finite element analysis, acoustics, and compressor and piping system design. He works primarily with large compressor systems for the natural gas transmission and petrochemical processing industry. Mr. White is an experienced mechanical analyst, designer, and project manager. Mr. White currently leads the Fluid Machinery Systems Section at SwRI, which is responsible for the design, analysis, and field testing of a variety of gas and liquid machinery piping systems.

ABSTRACT

Pump piping systems typically have small diameter branch connections that can develop vibration related fatigue failures due to mechanical excitation. Many installations do not take time to design small diameter piping to avoid this issue. However, the risk of fatigue failure of small diameter branch connections can be reduced using two alternative guidelines developed by the Energy Institute and GMRC/PRCI. This tutorial will show that the guidelines can be used in two ways. In the design stage, it will show the user how to design small diameter piping in a way that reduces the risk of vibration problems. For piping that is already installed, the tutorial will show the end user how to screen branch lines for susceptibility to fatigue failure and reduce or eliminate the vibration problems by adding clamps, changing the piping diameter, or changing the number or type of valves. Case studies of real world small bore piping connections will be used to demonstrate the method an end user would use to screen branch lines and, if necessary, reduce vibration problems in the piping and avoid future fatigue failures. Both guidelines will be applied to all case studies, and the resulting

recommendations will be compared to demonstrate the benefits, assumptions, and limitations of both guidelines and give the user a better understanding of the screening criterion used.

INTRODUCTION

Vibration of piping due to mechanical excitation is present in nearly any environment where small diameter branch connections (SBCs) of diameter size two inches and below are used. In initial piping designs, small diameter connections are often not considered or fully defined. While finite element techniques are often used to model the main piping system, it is time consuming and expensive to include all small bore piping. In addition, predictions of vibration and dynamic stress and strain amplitudes made using finite element models are subject to a range of uncertainty due to assumptions that must be made regarding the excitation sources, damping, restraint stiffness values, end conditions, etc.

There are two simpler approaches: the Energy Institute's (EI) "Guidelines for the Avoidance of Vibration Induced Fatigue and Process Pipework" and the Gas Machinery Research Council/ Pipeline Research Council International/ (GMRC/PRCI) "Design Guideline for Small Diameter Branch Connections" that can be used to reduce or avoid vibration problems in these small diameter connections without requiring a detailed study. The Energy Institute was founded in 2003 in the United Kingdom to merge the Institute of Petroleum and Institute of Energy into a combined organization supporting the energy sector by developing knowledge and best practices. GMRC is a gas machinery consortium funding research and guidelines to support overall industry concerns; on various topics, PRCI will co-fund GMRC research considered relevant and important to the members. This paper is written to simplify and clearly explain when and how to use each guideline so an individual can design small diameter branch connections that are less susceptible to fatigue failure due to vibration.

The key differences between the two guidelines are summarized as follows. The GMRC/PRCI guideline provides a way to estimate the mechanical natural frequency of the side branch connection to avoid a coincidence with the frequency of excitation in the main piping using a separation margin. However, it assumes that if a resonance is avoided, the likelihood of failure is low and, therefore, it does not consider fitting type, mainline risk factors, or the wall thickness of the branch or main line piping. The EI guideline assumes the user will calculate the mechanical natural frequency of the side branch to ensure there is no coincidence. Once the user is sure that a resonance will be avoided, this guideline considers a wide range of factors to quantify the robustness of the branch design.

There are two primary types of excitation in the main piping: discrete and broadband. Common sources of discrete excitation include pulsation from positive displacement pumps, impeller vane pass frequency, cavitation, and vortex shedding (Strouhal excitation). These sources can introduce a significant amount of energy in the system at each excitation harmonic. Broadband excitation, such as from high velocity flow turbulence, is typically of lower amplitude but spread over a wider frequency range.

Of these excitation sources, the pump system should simply not operate if cavitation is occurring, and this excitation should be resolved. Impeller vane pass frequency excitation and vortex-shedding excitation can cause very high pulsations and vibrations in the system, and it is best to find a solution (ideally in the design phase) rather than continue to operate a system with these problems. However, this is not always feasible; therefore if performance issues and cavitation (due to high pulsations) do not occur and stresses are relatively low, one can use these guidelines to ensure robust support of the small bore piping such that the risk of failure is reduced. Positive displacement pump excitation is unavoidable in the piping system as well as broadband flow turbulence from high velocity flows; for systems with these characteristics, the use of the guidelines for small bore piping design and review is valuable.

All structural systems will have multiple mechanical natural frequencies at which they will vibrate when impacted, much like a tuning fork. If the piping system is excited by a harmonic load such as pulsation or mechanical vibration at its mechanical natural frequency (resonance), then vibration amplitudes will be greatly amplified, often by a factor of between 10 and 50. Because of this high amplification that occurs during resonance, the simplest solution to most piping vibration problems is to avoid resonance. However, in cases where mechanical resonance cannot be avoided or where excitation forces are considered excessive, detailed structural modeling should be performed.

ENERGY INSTITUTE GUIDELINE

Scope and Limitations

The scope of this guideline is very broad and extends well beyond the limits of this paper. It is composed of various technical modules and supporting appendices on the assessment of the likelihood of failure (LOF) of the main line, small branch connections, and thermowells; visual assessments of piping and tubing; piping vibration measurement and predictive techniques; and corrective actions for the main line, SBCs and thermowells. This paper will only discuss technical modules T3 and T11, Quantitative SBC LOF Assessment and SBC Corrective Actions, respectively. Additional supportive information can also be found in Appendix C and Appendix D. The LOF is a unitless factor used for screening purposes. For SBCs, the screening criteria is as follows:

LOF ≥ 0.7 – The SBC shall be redesigned, resupported, or a detailed analysis shall be conducted

0.7 < LOF ≥ 0.4 – Vibration monitoring of the SBC should be undertaken.

LOF ≤ 0.4 – A visual survey should be undertaken to check for poor construction and/or geometry for the SBCs and instrument tubing.

A considerable drawback to using this guideline is that for discrete excitation, the most common sources of excitation, the structural natural frequency of the SBC would need to be measured or predicted using methods such as finite element analysis or experimental modal analysis. This is necessary to ensure there is not a coincidence between the structural natural frequency and the frequency of excitation. If a coupling between the two frequencies is predicted, the structural natural frequency should be shifted by either changing the stiffness or mass of the piping (adding a clamp, changing diameter, shortening the length, using a different type of valve). However, this requirement makes this guideline more difficult and time consuming to use.

Once it is determined that the frequency of excitation is sufficiently separated from the structural natural frequency, the guideline becomes a screening criteria for determining the robustness of the SBC design. The user can evaluate the effect of using different types of tee connections, wall thicknesses, number of valves, and various lengths. It provides a maximum span length between clamps to ensure a higher mechanical natural frequency of the SBC. For intermediate supports, the EI guideline assumes all clamps are to a deck or structural steelwork. To reduce the bending stress due to the displacement from vibration and thermal growth between the main line and the support, a minimum span length between the tee connection and the first clamp is also defined. This makes it a very comprehensive guideline that can be used for most side branches.

The guideline categorizes branch lines into four main categories

- Configuration 1 – Cantilever type
- Configuration 2 – Continuous—in and out same main line
- Configuration 3 – Continuous—with intermediate supports
- Configuration 4 – Continuous—between different main lines (with no intermediate supports)

Process

EI's guideline provides a series of flow charts used to calculate a LOF factor. The flowcharts in EIs guideline can be used as a broad-based screening criterion in the design phase of most small branch connections to determine which small branch connections are at risk for vibration problems. Weights are given to various characteristics of the small branch connection to evaluate its susceptibility to vibration and fatigue.

To simplify the process for performing the quantitative SBC LOF assessment, it can be done in isolation without going through the steps to determine the main line LOF. As stated in the guideline, a conservative LOF of 1 can be used for the main line to reduce the time and effort involved in reviewing each SBC in an installation and is the default used if there is any uncertainty in defining the characteristics (exact location of SBC in the main line, type and scope of excitation forces) used to determine the main line LOF. Note that this means that the LOF due to the placement of the SBC, $LOF_{LOC,}$ will also be 1 in the following process. Since the SBC modifier is determined by the minimum of the LOF of the SBC geometry, LOF_{GEOM}, and the LOF_{LOC}, the SBC LOF will be primarily determined by the SBC geometry, and this forces a more robust design of the SBC which is the primary goal.

The following process scores various properties of the SBC to determine an LOF. The characteristics taken into consideration are: type of fitting, length of the branch, number and size of valves, parent pipe schedule, and SBC diameter. The higher the natural frequency and the lower the stress concentration at the connection point, the less risk there is for vibration problems. Decreasing the length and increasing the diameter of the SBC raises the natural frequency of the SBC and, therefore, decreases the LOF score. Using fittings with lower stress intensification factors and risk of fatigue also decreases the LOF score. A thicker pipe schedule on the main pipe reduces the possibility of exciting shell modes and decreases the stress at the side branch connection. Configurations with intermediate supports have additional considerations such as the maximum length between supports and the minimum length between the first support and the main line.

The EI guideline states that the following step by step process should be followed:

Step 1: Determine SBC geometry type

- This includes categorizing the branch line in question into one of the four configurations described in Flowchart T3-1 cantilever, continuous, continuous with intermediate supports, or continuous between main lines with intermediate supports (Figure 1).

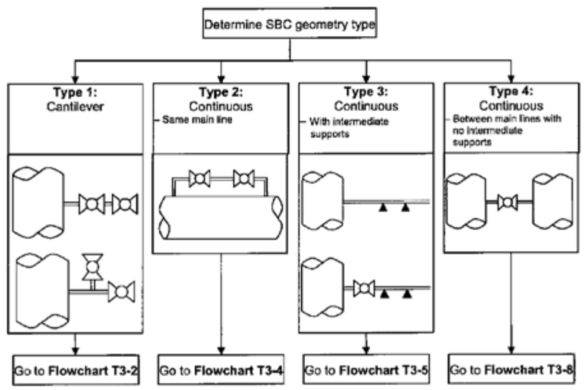


Figure 1. SBC Geometry Types (Flowchart T3-1 in EI Guideline)

Step 2: Use provided flowcharts T3-2, T3-4, T3-5 or T3-8 associated with each geometry type to determine SBC geometric LOF_{GEOM}

- The method to calculate these values is dependent on the geometry type selected in Step 1. All geometry types will use Flowchart T3-3 to determine the SBC geometric LOF_{GEOM}. This flowchart assigns values for different factors such as type of fitting, branch length, main line pipe schedule, branch line pipe schedule, and number of valves. For Type 2 and Type 4, the branch is divided into halves, and a value is determined for each section of the branch.
- In addition to the SBC geometric LOF_{GEOM} from Flowchart T3-3, geometry Type 3 and Type 4 also determine a minimum and maximum allowable span length for spans with and without masses.
- All SBC geometric LOF_{GEOM} values determined from the steps above are compared to determine the final branch SBC geometric LOF_{GEOM}.
- A simplified chart showing the tables and flowcharts needed to analyze each configuration is shown in Figure 2 below.

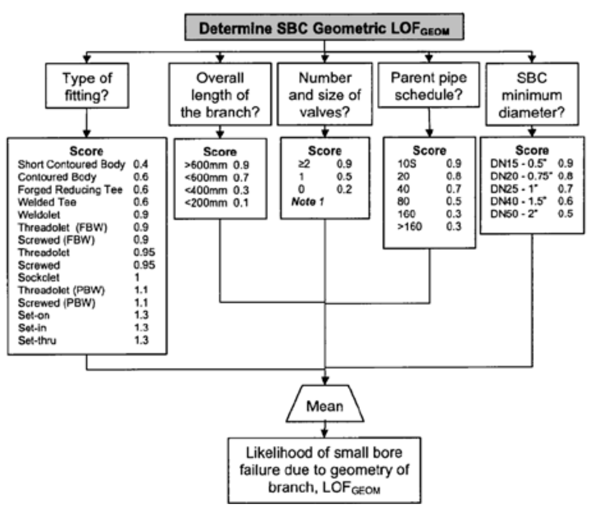


Figure 2. Flowchart T3-3 from the EI Guideline

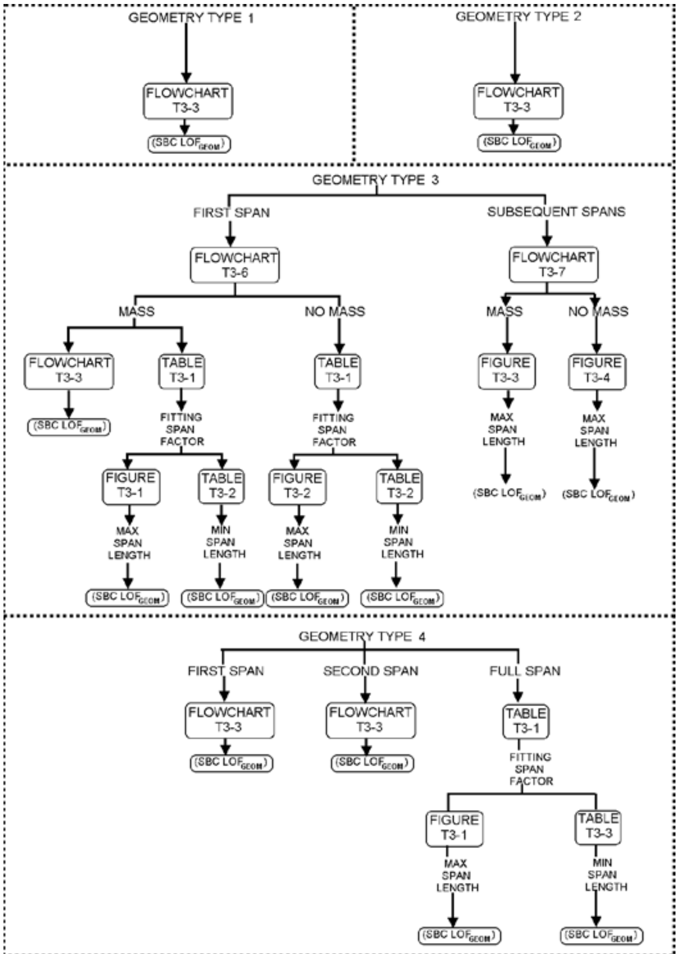


Figure 3. Simplified Flow Charts Showing SBC Geometric LOF_{GEOM} Values for Each Configuration

The assumption above that the main line LOF = 1, allows us to skip steps 3 through 5, since the SBC LOF = SBC Modifier = LOF_{GEOM}

Step 3: Determine SBC Modifier where SBC Modifier = Minimum [LOF_{GEOM}, LOF_{LOC}]
Step 4: Multiply the Main Line LOF by 1.42 (1x1.42=1.42) to get Main Line LOF
Step 5: Use the Minimum [Main Line LOF, SBC Modifier] to determine SBC LOF
Step 6: Determine if corrective action is needed and develop modifications to reduce LOF

Notes:

- Dimension of SBC taken from outer wall of main piping
- Use the most conservative value if fitting type is not clear, schedule is not listed, or multiple diameters/lengths,
- Use Section C.1.2 for flange/valve ratings of ANSI 900 or higher
- Use the smallest diameter for the most conservative score if diameter changes in the SBC,
- If splitting a connection into two segments and mass is near the midpoint, assess each segment with the mass at the end of each one.

It is important to note that a small branch connection connected on each end to a different main line (configuration type 4 - continuous between main lines with intermediate supports) can be subject to high static stress from the thermal growth of the two main lines. It is not recommended that this configuration be used without thermal analysis of the stresses. Adding a clamp to this configuration will change it to a configuration type 3 (continuous with intermediate supports) and is recommended. There will still be a risk of static stress; however, the guideline lowers that risk in its consideration of the minimum length between the first support and the main line.

As mentioned above, all geometry types refer to Flowchart T3-3 shown below. This flowchart provides an SBC Geometric LOF_{GEOM} for each branch and will determine the final SBC Geometric LOF_{GEOM} for cases where the unsupported span lengths are within the minimum and maximum allowable lengths. Because of the importance of this flowchart to the EI guideline, it is recommended the user becomes familiar with this flowchart to understand the sensitivity the SBC Geometric LOF_{GEOM} has to each factor.

- Type of Fitting: The type of connection between the branch line and main line can significantly lower the $LOF_{GEOM.,}$ however changing from a threadolet to a weldolet does not produce a large drop, and resources may be better used elsewhere.
- Overall length of branch: The overall length of the span in question is given a score where the longer the span the higher the resulting LOF_{GEOM} will be. To obtain a low score, the span length needs to be less than approximately two feet. This is often not a feasible option to reduce the LOF_{GEOM}, and a score of 0.9 is likely used for most branches.
- Number and size of valves: The values shown in Flowchart T3-3 are for valve ratings below ANSI 900. A lightweight integral valve can be treated as a single valve. The difference between one and two valves is large and can significantly raise the LOF_{GEOM} value. All types of valves, both large and small, are given the same weight and the score may be very conservative for smaller valves. The type of valve that is considered and may be very conservative for smaller valves is not clearly defined.
- Parent pipe schedule: The pipe schedule of the main line can affect the vibration of the branch line as a thicker wall would provide a more stable base to the branch.
- SBC minimum diameter: The minimum diameter of a branch is often determined by process conditions or fitting sizes. A larger diameter does provide a lower score but the benefit may be marginal, if only a small diameter change is possible.

GMRC/PRCI GUIDELINE

Scope and Limitations

The GMRC/PRCI guideline is a more specific guideline designed for use in evaluating small branch connections in pump piping systems. The design philosophy for this guideline is to reduce risk by placing the lowest mechanical natural frequency of the branch connection above the frequencies of most significant excitation occurring at the base of the branch line. In addition, a secondary non-resonant stress criterion is also included to take into account dynamic stress (and strain) when there is significant vibration in the mainline. This guideline provides recommendations on unsupported span lengths with and without added masses such as valves in order to minimize the possibility of fatigue failure. The guideline is meant to be quick and easily used with few calculations and no special instrumentation or software to evaluate and reduce vibration problems in SBCs.

Rather than having to predict the structural natural frequency of the SBC, the guideline delineates an area on a graph showing what range of lengths and masses will raise the structural natural frequency sufficiently above the primary excitation frequencies to avoid a coincidence. In most cases, the lowest mechanical natural frequency of the branch should be at least 20% above the first, second, or fourth multiple of the pump running speed (guidance on frequency selection is included in the guideline). Not having to calculate the structural natural frequency is a significant advantage, especially when evaluating a large quantity of SBCs. This guideline is primarily suggested for use to screen for potential vibration problems where the mechanical natural frequency of the SBC is unknown. A quick visual check of the appropriate graph can give the user the option to choose whether changing the length, diameter, or weight of the SBC is the best option to stay inside the limitations of the line on the graph and how much to change each factor.

This guideline states that the vibration excitation sources considered are limited to centrifugal and reciprocating pumps (and compressors). However, it can also be used for slower speed screw pumps if the design frequency (typically 20% above the key order) is 200 Hz or lower. The steps used would be identical to that of a reciprocating compressor.

For centrifugal pumps, the guideline design frequency for SBCs is 15 Hz. Since mechanical natural frequencies for all SBCs should be designed to exceed 15 Hz to significantly reduce the risk of vibration from low frequency broadband excitation sources, this guideline can be extended for the use for SBCs in meter stations and other areas where flow turbulence excitation is a primary concern. More broadly, all structural natural frequencies should be at least 10 Hz for straight horizontal spans and closer to 15Hz for all other configurations to reduce the likelihood of excitation. It is important to note that the authors of this guideline recommend using caution installing SBCs within 25 feet of the centrifugal compressor. It has been their experience that there is often high frequency excitation of the shell modes of the piping which can cause small bore piping connection failures.

The guideline provides specifications for ten different excitation or design frequencies (related to operational speed). The determination of the frequency for the connection selection is discussed in the guideline. Ten different design frequencies are included: 15, 24, 30, 40, 48, 60, 80, 96, 144, and 200 Hz. Under each of these frequencies, recommendations for the branch geometries are provided for each of the six SBC configurations. Each of the recommended geometries covers multiple nominal branch diameters (½", ¾", 1", 1 ½", and 2") and indicates the maximum acceptable length of the branch based on the weight of the branch. Select configurations also include information for Long Welding Neck (LWN) nozzles.

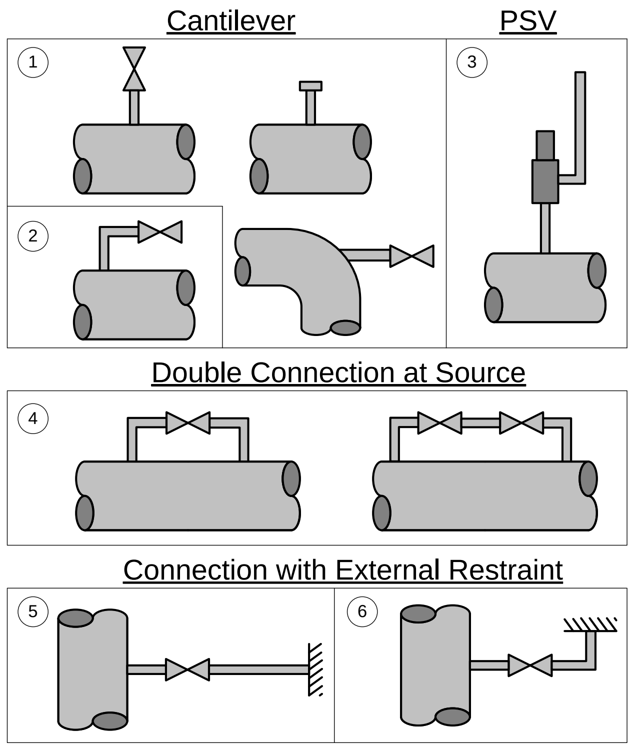


Figure 4. Images of Various Branch Connection Configurations

The GMRC/PRCI guideline provides recommendations for branch connections with nominal pipe diameters equal to or less than two inches, and where the nominal branch diameter to main pipe diameter ratio is less than 25%. This guideline covers six different configurations. It also recommends that supports added to the branch line to raise the natural frequency will be braced back to the main line. However, if this is not possible, then using the minimum span length allowable in the EI guideline is important for clamp placement. This guideline covers only the six different configurations as described below and shown in Figure 4.

- Configuration 1 – Straight cantilever (with or without LWN)
- Configuration 2 – Cantilever with elbow
- Configuration 3 – Pressure safety valve (PSV) (with or without LWN)
- Configuration 4 – Double connection at source
- Configuration 5 – Straight connection with external restraint
- Configuration 6 – Connection with external restraint with elbow

Process

The guideline is used by reading allowable weight and/or length values from a series of included graphs. Different graphs are included for various configuration types and design frequencies. Each graph has multiple curves for each nominal piping diameter (1/2" through 2").

The following step by step process should be followed:

Step 1: Define equipment type (reciprocating/ centrifugal /screw pump)
Step 2: Determine if branch is "near" or "far" from excitation source

- For centrifugal pumps, “near” is considered within 25 feet.
- For reciprocating pumps “near” is considered within 20 ft.

Step 3: Determine design frequency

- The design frequency is typically 20% above key excitation order. Table 1 summarizes provides the design frequency for a number of speeds and equipment.

Table 1. Design Frequencies for Various Operating Conditions (Table 3-1 of GMRC/PRCI Guideline)

RPM	Centrifugal Pump		Centrifugal Compressor		Reciprocating Compressor		Reciprocating Pump: 1 plungers		3 plungers		5 plungers		7 plungers	
	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far	Near	Far
330					26.4	13.2	13.2	6.6	39.6	19.8	66	33	92.4	46.2
750					60	30	30	15	90	45	150	75	210	105
1000					80	40								
1200					96	48								
1800	72	15			144	72								
3600	144	15												
5000	200	15												
> 5000	N/A*	15	N/A**	15										

* Note: Calculate for specific speed as described in guideline.
** Note: Requires detailed analysis which is not covered by this guideline

- Step 4: Select design frequency section of guideline (round frequency up)
- The guideline is divided into ten design frequency sections: 15, 24, 30, 40, 48, 60, 80, 96, 144, 200 Hz.
- Step 5: Select configuration type as shown in Figure 5 and determine the effective lengths (Le) (as shown in the figures below).
- Step 6: Determine branch nominal diameter (0.5”, 0.75”, 1”, 1.5” or 2”)
- Step 7: Use graphs to determine allowable weight and length

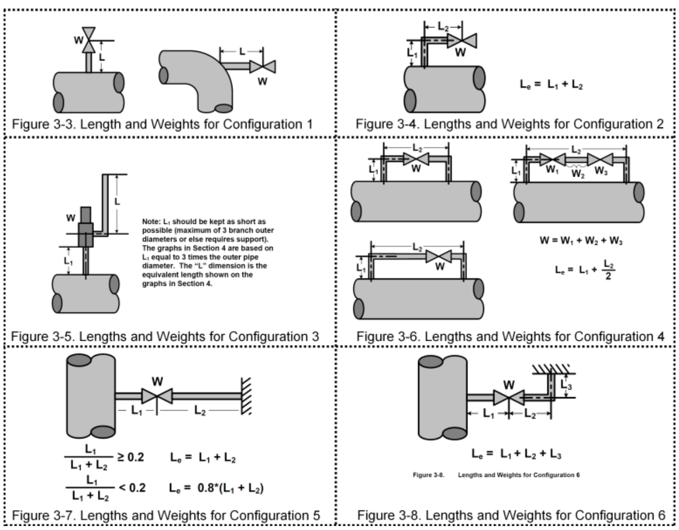


Figure 5. How to Determine the Effective Length of an SBC--Figures 3-3 through 3-8 from the GMRC/PRCI Guideline

The guideline itself includes a detailed explanation of each step described above. Figure 6 below shows a typical sample graph. Due to the number of graphs, all cannot be presented here but can be found in Section 4 of the guideline.

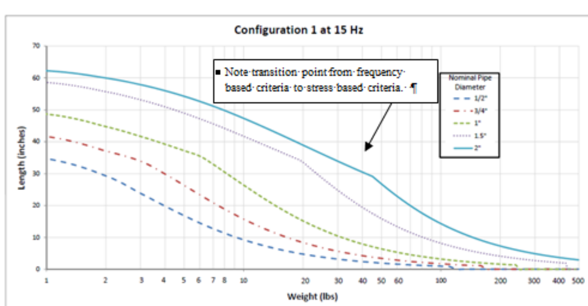


Figure 6. Sample Graph of a Branch Connection Configuration from GMRC/PRCI Guideline

If the characteristics of the SBC are not below the area circumscribed by the appropriate curve, the user can either shorten the length of the branch connection, use a different valve type that has a lower weight, decrease the number of valves on the line to decrease the weight, or add a support to change the type of configuration.

CASE STUDIES

For the following case studies, all diagrams and graphs are taken from the "Guidelines for the Avoidance of Vibration Induced Fatigue in Process Pipework" published by EI and "Design Guidelines for Small Diameter Branch Connections" published by GMRC/PRCI and are reprinted with permission.

Case Study #1

A centrifugal pump had ¾-inch nominal diameter schedule 80 vent piping that failed at the weldolet connection to the 8-inch main line as shown in Figure 7. A metallurgical analysis concluded the failure was due to high cycle fatigue. There was significant mechanical vibration in the main line, high velocity flows, and high displacement measured near the elbow on the branch connection. The first mechanical natural frequency of the piping was measured to be approximately 13 Hz; this is flexible enough to have a high risk of excitation if significant vibration is seen in the pump case. SwRI was asked to either recommend bracing or redesign the line to reduce the risk of failure. This branch will be analyzed using both guidelines described above to test if either or both guidelines would recommend a redesign and could have prevented the failure from occurring.

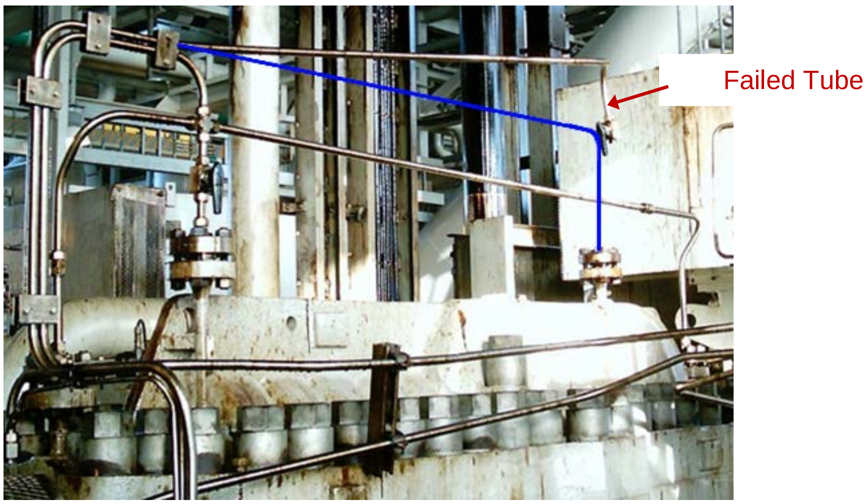


Figure 7. Case Study 1: A Small Bore Piping Failure

Using the GMRC/PRCI Guideline

Design Frequency: 15 Hz (Minimum excitation frequency for ALL small bore piping connections)

Configuration Type: Configuration Type #6

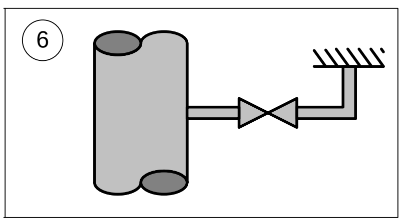


Figure 8. Configuration Type 6 from PRCI-GMRC Guideline

Branch Nominal Diameter: ¾-inch

GMRC/PRCI Recommendation: Using the plot found on page 21 of the guideline and a weight of 1, since there are no valves or flanges, the clamp should be located no more than 70 inches from the main line pipe wall.

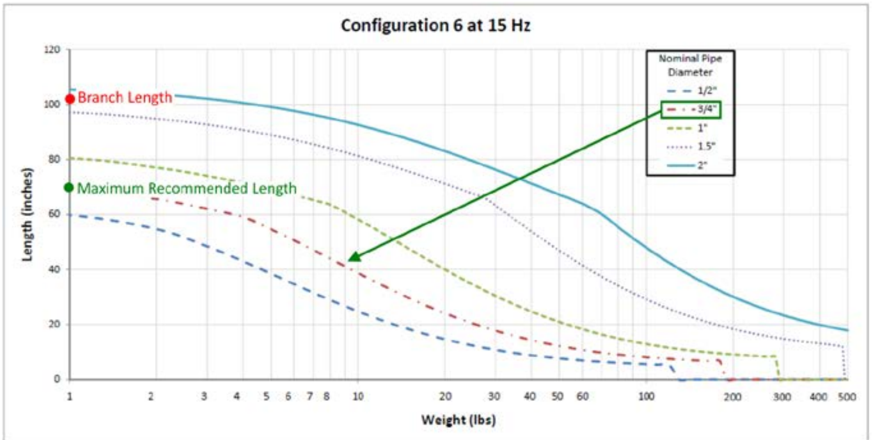


Figure 9. Graph Providing Maximum Span Lengths for Configuration Type 6

The original clamp was placed over 100 inches from the main line pipe. The GMRC/PRCI Guideline recommends shortening the length of the unsupported span by rerouting the tubing or adding a clamp or brace.

Using the EI Guideline

Step 1: Configuration 2 selected

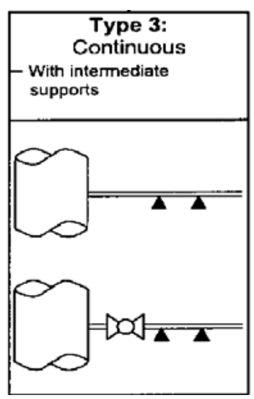


Figure 10. Configuration Type 3 from EI Guideline

Step 2: Use Flowchart T3-5 to determine the maximum LOF_{GEOM}

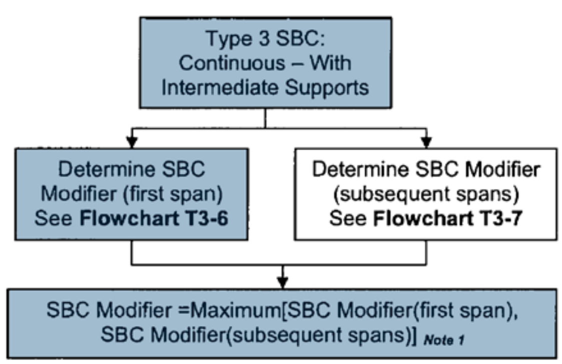


Figure 11. Flowchart T3-5 for Configuration Type 3 Analysis

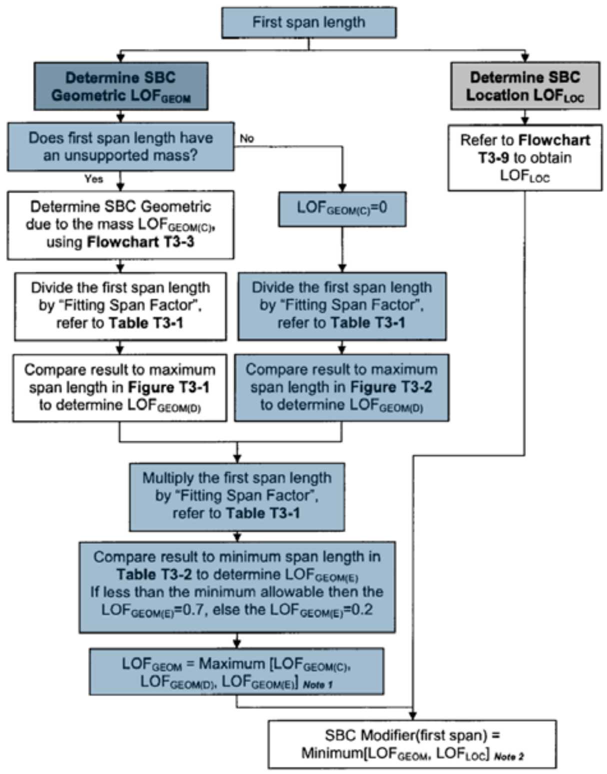


Figure 12. Flowchart T3-6 for Calculating LOF for Type 3 Configurations

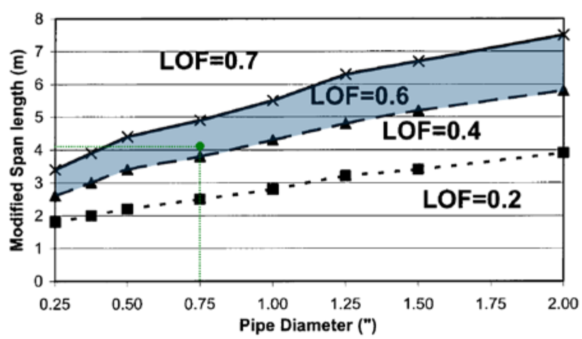


Figure 13. Maximum Span Length for Span Connected to Main Line with No Additional Mass (Figure T3-2 from EI Guideline)

Table 2. LOF Values for Case Study #1

Configuration 3	Value	LOF
Fitting Span Factor	0.65	
Equivalent Maximum Span Length	4.1 m	0.6
Equivalent Minimum Span Length	1.7 m > 0.9 m allowable	0.2
LOF_{GEOM} (maximum of above LOF)		0.6

Step 6: Determine corrective action

EI Recommendation: The pipe should be monitored for vibration and possibly redesigned.

It is interesting to note that the EI guideline is less conservative and allows more flexible piping. It does not strongly indicate that there is a potential for vibration problems given the length between the main line connection and the first support, even though the piping has a mechanical natural frequency of less than 15 Hz. However, to reduce a LOF score that indicates a need for caution, one can decrease the maximum span length by placing a clamp closer to the main line connection. This demonstrates that while these guidelines are useful in detecting branch lines which are susceptible to vibration, detailed analysis or field measurements are much more accurate and consistent in detecting vibration issues.

Final Recommendation: Brace the vertical section of the pipe near the elbow back to the main line. This is the ideal location, as the displacement would be highest at this flexible joint. A concept of the type of support recommended for this branch is shown in Figure 14.

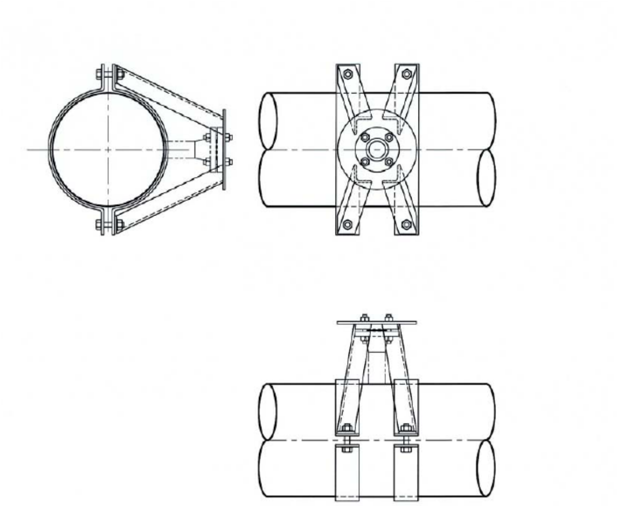


Figure 14. Small Bore Bracing Concept

Case Study #2

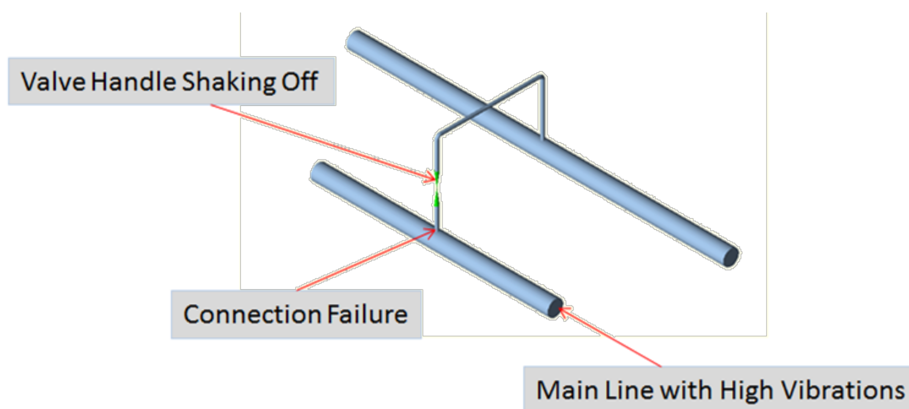


Figure 15. Case Study 2—Small Bore Piping Vibration Problem

A pump piping system had high vibrations near the pump due to impeller vane pass frequency exciting an internal passage length. This resonance transmitted high vibrations into the piping resulting in a failure of a small bore piping connection not well-supported. Until the resonance could be eliminated in the system (major changes would need to be made to the pump internals), SwRI created a more robust mechanical design for the small bore piping configuration to allow temporary continued operation of the pump with a reduced likelihood of failure. The 6” diameter main line with a 1-inch diameter branch was experiencing high vibration. The branch was connected with a weldolet and runs through a valve to another line. The valve handle had fallen off due to high vibrations and cracks occurred at the weld seams.

Using the GMRC/PRCI Guideline

Design Frequency: 15 Hz (Minimum excitation frequency for ALL small bore piping connections that typically allows for a robust design)

Configuration Type: Configuration Type #6

Branch Nominal Diameter: 1-inch

Le = 110 in = 2.8 m

Weight = 35 lbs

GMRC/PRCI Recommendation: Using the plot found on page 23 of the guideline and a weight of 35lbs for the valve, the clamp should be located no more than 26 inches from the main line pipe wall.

Figure 16. Graph Providing Maximum Span Lengths for Configuration Type 6 from GMRC/PRCI Guideline

The original span length was approximately 110 inches from the main line pipe. The GMRC/PRCI guideline recommends adding an additional clamp or brace.

Using the EI Guideline

Step 1: Configuration 4 selected

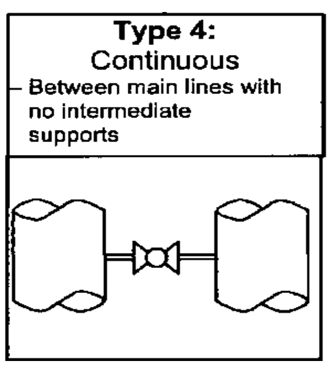


Figure 17. Configuration Type 4 from EI Guideline

Step 2: Use Flowchart T3-8 to determine the maximum LOF_{GEOM}

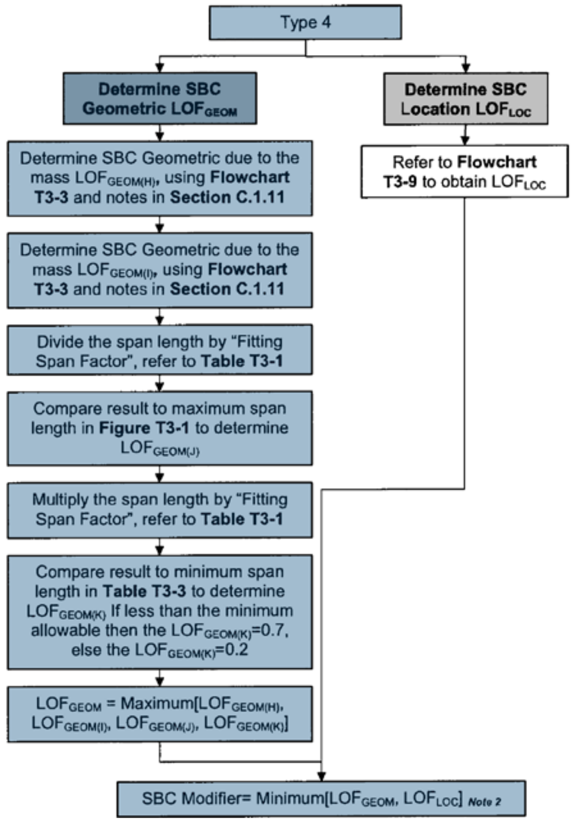


Figure 18. Flowchart T3-8 for Calculating LOF for Type 4 Configurations

The provided flow chart determines a number of LOF factors based on a number of branch parameters.

- $LOF_{GEOM(H)}$- Likelihood of failure of first span length
- $LOF_{GEOM(I)}$ - Likelihood of failure of second span length
- $LOF_{GEOM(J)}$ - Likelihood of failure of total span length compared to maximum span length
- $LOF_{GEOM(K)}$ - Likelihood of failure of total span length compared to minimum span length

If any LOF factors are considered high, the branch is considered likely to fail. The branch is broken into two spans to evaluate its characteristics such as mechanical natural frequencies, fitting connections and parent pipe schedule (stress intensification factors). It is also evaluated for,

$LOF_{GEOM(H)}$ of first span from valve to main line from Flowchart T3-3 = 0.7:

L1 (length from main line to valve) = 19" = 482.6 mm

L2 = 91" = 2311 mm

Table 3. Flowchart T3-3 LOF Values for First Span of Original Layout

Category	Value	Flowchart T3-3 Score
Type of Fitting	Weldolet	0.9
Overall Length	482.6 mm	0.7
Number and Size of Valves	1	0.5
Parent Pipe Schedule	80	0.5
SBC Minimum Diameter	1	0.7
Mean of Above Scores ($LOF_{GEOM(H)}$)		0.7

$LOF_{GEOM(I)}$ of first span to valve from Flowchart T3-3 = 0.7:

Table 4. LOF Values for Second Span of Original Layout

Category	Value	Flowchart T3-3 Score
Type of Fitting	Weldolet	0.9
Overall Length	2311 mm	0.9
Number and Size of Valves	1	0.5
Parent Pipe Schedule	80	0.5
SBC Minimum Diameter	1	0.7
Mean of Above Scores ($LOF_{GEOM(I)}$)		0.7

$LOF_{GEOM(J)}$ from span length/span factor = 2.8/0.7 = 4 compare to Figure T3-1 = 0.7

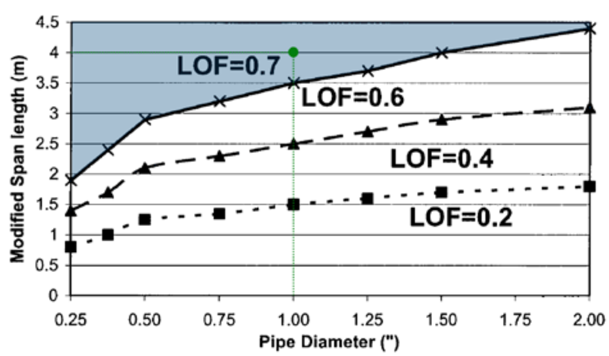


Figure 19. Maximum Span Length for Span Connected to Main Line with Additional Mass (Figure T3-1 from EI Guideline)

$LOF_{GEOM(K)}$ from from Table T3-3.

$$Span\ length\ \times span\ factor = 2.8\ \times 0.7 = 1.96$$

From Table T3-3 minimum allowable = 1.6

$1.96 > 0.6 \therefore$ $LOF_{GEOM(K)}$ = 0.2 (not likely to fail from thermal growth)

$LOF_{GEOM} = Max (LOF_{GEOM(H)}, LOF_{GEOM(I)}, LOF_{GEOM(J)}, LOF_{GEOM(K)}) = 0.7$

Table 5. Final LOF Values for Case Study 2 for Original LayoutConfiguration 4

	LOF
$LOF_{GEOM\ (H)}$	0.7
$LOF_{GEOM\ (I)}$	0.7
$LOF_{GEOM\ (J)}$ - Equivalent Maximum Span Length	0.7
$LOF_{GEOM\ (K)}$ - Equivalent Minimum Span Length	0.2
LOF_{GEOM} - (maximum of above LOF)	**0.7**

Step 6: Determine Corrective Action

EI Recommendation: The SBC shall be redesigned, re-supported, or a detailed analysis shall be conducted

Both the GMRC/PRCI guideline and the EI guideline determine that this branch is susceptible to high vibration and remedial action should be taken. Adding a restraint to the branch would change the configuration on the EI guidelines from a Type 4 to a Type 3. As mentioned in the previous section, Type 4 configurations often experience high thermal stress levels or low natural frequencies and are typically not recommended. According to the guideline, bracing the SBC *back to the main line* would result in a branch having a shortened span length as described in Section C.1.6. The span length would then start at the brace and the mass of the valve is ignored as shown in Figure 20.

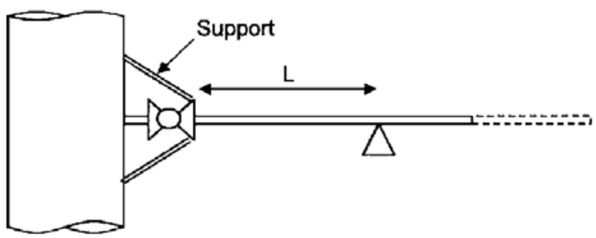


Figure 20. Example of Bracing Branch Back to Main Line as Shown in EI Guideline

For a brace of the valve back to the main line the LOF is calculated as follows.

$LOF_{GEOM(H)}$ of first span up to valve from Flowchart T3-3 = 0.6:

L1 = 91" = 2311 mm

Table 6. Flowchart T3-3 LOF Values for Recommended Layout

Category	Value	Flowchart T3-3 Score
Type of Fitting	Weldolet	0.9
Overall Length	2311 mm	0.9
Number and Size of Valves	0	0.2
Parent Pipe Schedule	80	0.5
SBC Minimum Diameter	2	0.5
Mean of Above Scores($LOF_{GEOM(I)}$)		0.6

$LOF_{GEOM(J)}$ from span length/span factor = 2.3/0.7 = 3.3 compare to Figure T3-1 = 0.6

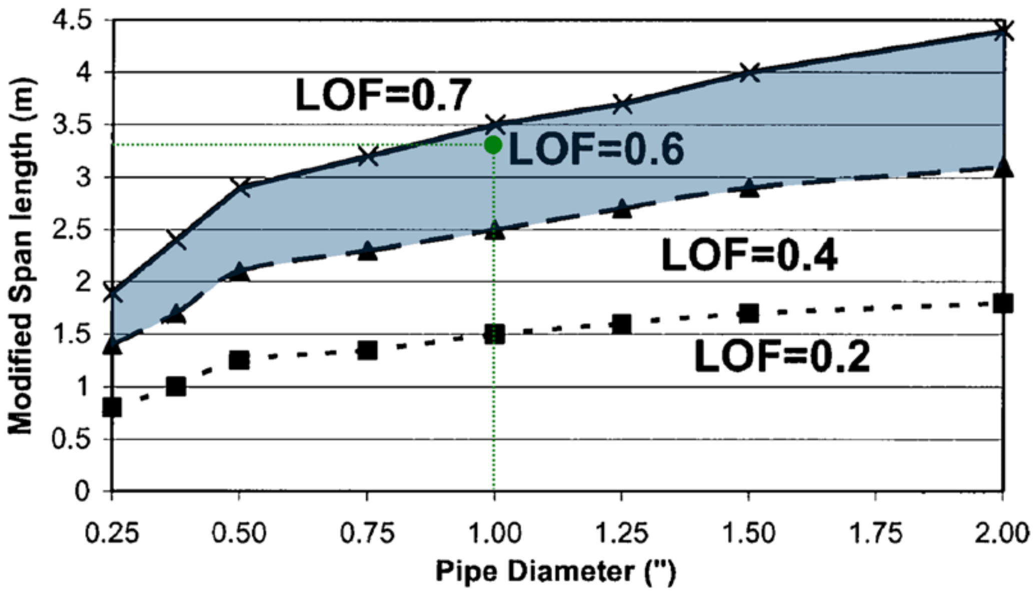


Figure 21. Maximum Span Length for Span Connected to Main Line with Additional Mass (Figure T3-1 from EI Guideline)

$LOF_{GEOM(K)}$ from from Table T3-3.

$$Span\ length\ \times span\ factor = 2.3\ \times 0.7 = 1.61$$

From Table T3-3 minimum allowable = 1.6

$1.61 > 0.6 \therefore$ $LOF_{GEOM(K)}$ = 0.2 (not likely to fail from thermal growth)

Table 7. Final LOF Values for Recommended Layout

Configuration 4	LOF
$LOF_{GEOM\ (H)}$	0.6
$LOF_{GEOM\ (I)}$	0.6
$LOF_{GEOM\ (J)}$ - Equivalent Maximum Span Length	0.6
$LOF_{GEOM\ (K)}$ - Equivalent Minimum Span Length	0.2
LOF_{GEOM} - (maximum of above LOF)	**0.6**

Step 6: Determine Corrective Action

It is recommended that the pipe should be monitored for vibration and possibly redesigned. To verify the findings from the preliminary screenings, field measurements of this branch were acquired, and it was found the natural frequency of this branch was 14.7 Hz. Note that both guidelines conservatively recommended additional support for this branch based on its configuration. Since the natural frequency is slightly below the critical frequency of 15 Hz, additional bracing was confirmed as the final recommendations, and worked for this system until the main line vibration problems could be resolved.

Final Recommendation: Brace the horizontal section of the pipe near the valve back to the main line. This is the ideal location as the large mass should be supported.

Case Study #3

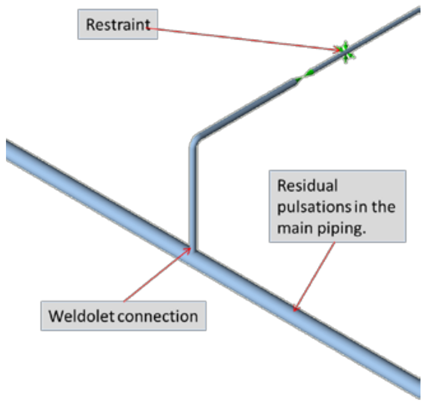


Figure 22. Case Study 3—Small Bore Piping Screening

A triplex reciprocating offshore pump system operating at 270 rpm has an 8” schedule 60 line with a 2” recirculation branch near the pump connected with weldolets. High vibrations were reported on the branch line. While the pump system had a gas-liquid dampener installed to damp pulsations, residual pulsations at 3x and 6x running speed (first “plunger speed”) were still present in the system and could excite piping with low mechanical natural frequencies. There was little space available for support foundations. Station personnel had concerns that failures could occur.

Using the GMRC/PRCI Guideline

Design Frequency: 30 Hz (~20% above two times plunger speed)

Configuration Type: Configuration Type #6

Branch Nominal Diameter: 2-inch

L1 = 54 in = 1372 mm (Length from weldolet to elbow)

L2= 59 in = 1499 mm (Length from elbow to valve)

L3= 24 in = 607 mm (Length from valve to restraint)

Le = L1+L2+L3 = 137 in = 3480 mm

Weight 1=60 lbs

GMRC/PRCI Recommendation: Using the plot found on page 31 of the guideline and a weight of 60 lbs for the valve weight, the clamp should be located no more than 40 inches from the main line pipe wall as shown in Figure 23. The piping should have a clamp near the weldolet that is braced back to the main line for additional stiffness.

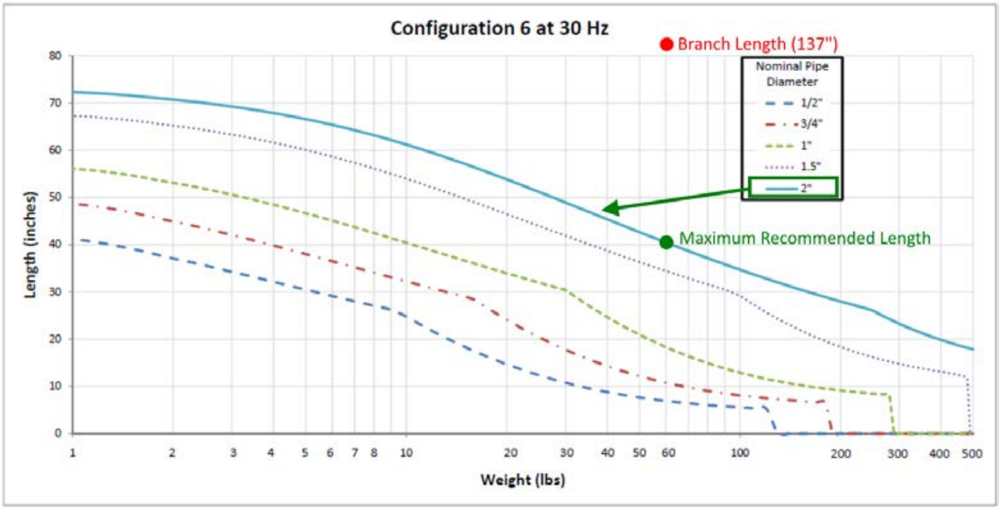


Figure 23. Graph Providing Maximum Span Lengths for Configuration Type 6 from GMRC/PRCI Guideline

Using the EI Guideline

Step 1: Configuration 3 selected

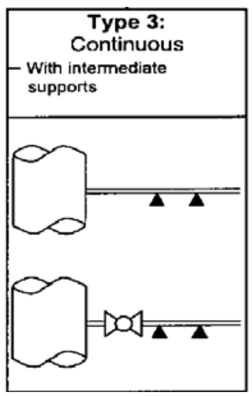


Figure 24. Configuration Type 3 from EI Guideline

Step 2: Use Flowchart T3-5 to determine the maximum LOF_{GEOM}

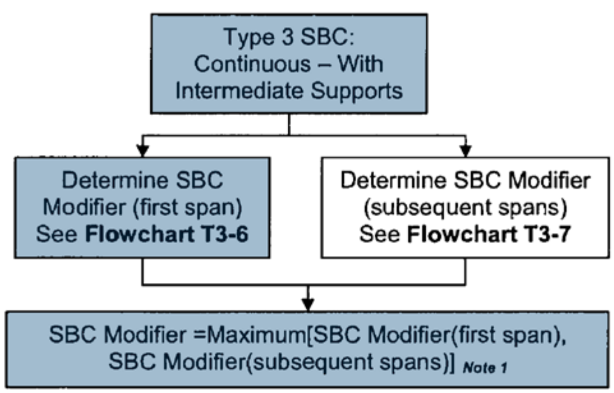


Figure 25. Flowchart T3-5 for Configuration Type 3 Analysis

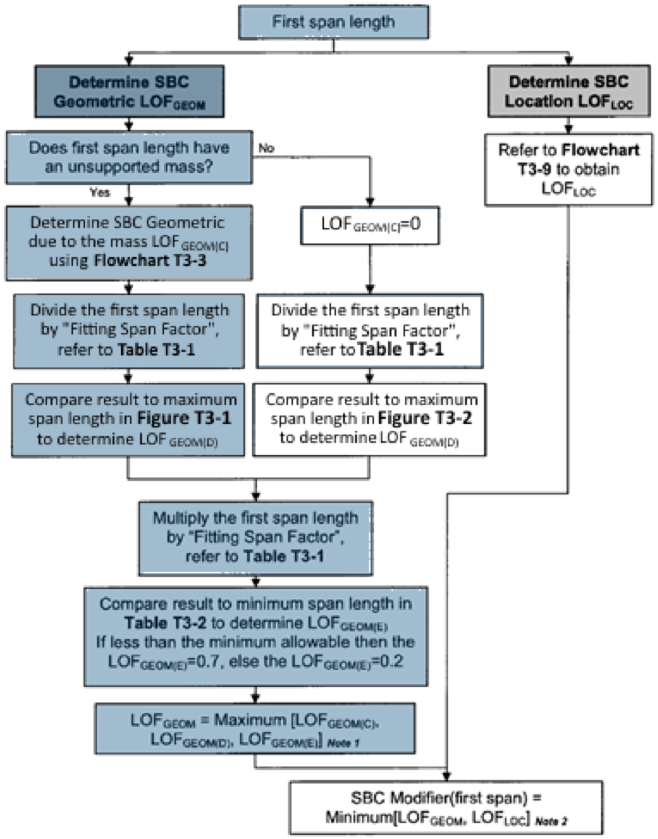


Figure 26. Flowchart T3-6 for Calculating LOF for Type 3 Configurations

$LOF_{GEOM(C)}$ of first span up to valve from Flowchart T3-3 = 0.7:

L1 = 137” = 3480 mm

Table 8. Flowchart T3-3 LOF Values for Recommended Layout

Category	Value	Flowchart T3-3 Score
Type of Fitting	Weldolet	0.9
Overall Length	3480 mm	0.9
Number and Size of Valves	1	0.5
Parent Pipe Schedule	60	0.7
SBC Minimum Diameter	2	0.5
Mean of Above Scores($LOF_{GEOM(C)}$)		0.7

$LOF_{GEOM(D)}$ from span length/span factor = 3.4/0.7 = 4.9 compare to Figure T3-1 = 0.7

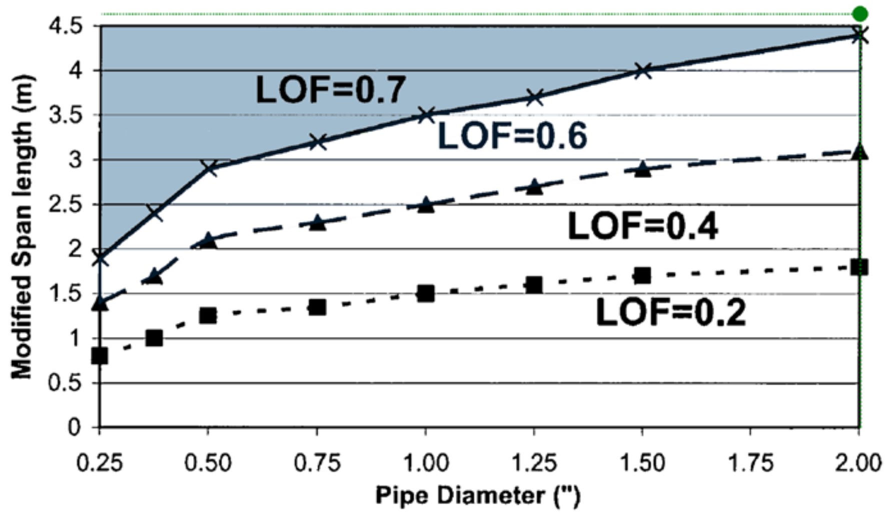


Figure 27. Maximum Span Length for Span Connected to Main Line with Additional Mass (Figure T3-1 from EI Guideline)

$LOF_{GEOM(E)}$ from from Table T3-3.

$$Span\ length\ \times span\ factor = 3.48\ \times 0.7 = 2.4$$

From Table T3-3 minimum allowable = 1.4

$2.4 > 1.4 \therefore$ $LOF_{GEOM(K)}$ = 0.2 (not likely to fail from thermal growth)

LOF_{GEOM} = Max ($LOF_{GEOM(C)}$, $LOF_{GEOM(I)}$, $LOF_{GEOM(D)}$, $LOF_{GEOM(E)}$) = 0.7

Table 9. Final LOF Values for Case Study 3 for Original Layout Configuration 3

	LOF
$LOF_{GEOM\ (C)}$	0.7
$LOF_{GEOM\ (D)}$	0.7
$LOF_{GEOM\ (E)}$ - Equivalent Minimum Span Length	0.2
LOF_{GEOM} - (maximum of above LOF)	**0.7**

Step 6: Determine Corrective Action

EI Recommendation: The SBC shall be redesigned, re-supported, or a detailed analysis shall be conducted

Both the GMRC/PRCI guideline and the EI guideline determine that this branch is susceptible to high vibration and remedial action should be taken. Adding a restraint to the branch on the other side of the valve would remove the mass of the valve from the span lowering the LOF to 0.6. If the branch is supported near the weldolet the LOF can be lowered even further. According to the guideline, bracing the SBC back to the main line would result in a branch having a shortened span length as described in Section C.1.6.

BEST DESIGN PRACTICES FOR SMALL BORE PIPING

Piping Design

- Small bore piping wall thickness should be schedule 80 or higher

- Fittings with higher stress concentration factors (such as threaded connections) should be avoided in higher risk areas such as “near” the compression equipment. Therefore, weldolets are preferable over threadolets.
- Branch line lengths should be kept as short as possible with minimal attached weight to raise the structural natural frequency
- If possible, locate the branch line away from valves, reducers, bends and tees in the main line where flow turbulence and acoustic induced vibration may cause problems
- Threaded fittings should be tight and back welded such that there are no exposed threads; threadolets are generally not recommended.
- Standard or higher schedules are recommended for main line piping to reduce the stress concentration at the connection to the SBC.

Restraints

The installation of an external restraint (support, bracing, etc.) will add stiffness to the branch line, raising its minimum mechanical natural frequency and reducing the risk of excessive vibration. Because there are an almost unlimited number of potential branch line configurations, it is not possible to recommend specific restraint configurations that will cover all feasible layouts. However, the following general guidelines are provided.

- The stiffer the restraint, the more effective it will be. A minimum restraint stiffness of 10,000 lbf/in in all three translational directions is recommended.
- A good restraint should be triangulated in multiple planes to provide stiffness in multiple directions. A restraint mounted to a tall, single slender support will typically be very flexible and ineffective in controlling vibration in directions other than the axial direction of the tall support.
- Simple weight supports and springs typically provide very little vibration control.
- It is typically preferred to brace the branch line back to the mainline piping. Bracing the branch line to a very stiff external support can increase bending stresses due to relative displacement from vibration and thermal expansion. A relatively stiff external support should not be installed too close to the branch connection.
- Strap type clamps are typically more effective than U-Bolt type restraints. If U-Bolts are used, they should be used in pairs to prevent rotation about the u-bolt.
- Gusset plates can add stiffness but also add high stress intensification factors and should be used with caution. If used, any gussets should attach to a reinforcing pad and not directly to the mainline.
- To prevent fretting, all clamps should be lined with a resilient liner material (Fabreeka or similar).

REFERENCES

Design Guideline for Small Diameter Branch Connections, Release 1.0, GMRC-PRCI, March 2011.

Guidelines for the Avoidance of Vibration Induced Fatigue and Process Pipework, 2nd Edition, Energy Institute, January 2008.